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The effect of cutting speed and feed rate on the surface integrity in dry turning of CoCrMo alloy

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Abstract

CoCrMo alloy is a high-wear resistant and biocompatible material currently utilized in the production of medical implants, which are cast or forged, and then machined to final dimensions. The machining step is usually conducted under conventional lubricating conditions, forcing to costly and time-consuming cleaning steps. On the contrary, to machine under dry lubricating conditions could modify the part surface characteristics, which, in turn, could have remarkable effects on the part functional requirements. The objective of the paper is to investigate the effect of process parameters on the surface integrity of CoCrMo alloy bars subjected to longitudinal turning under dry conditions. The surface integrity was investigated in terms of (i) surface finish; (ii) sub-surface microstructure refinement and micro-hardness; (iii) residual stresses. The presented results show that under certain conditions the part surface integrity is not altered by the dry conditions.

Keywords: Cobalt; Turning; Surface integrity

1. Introduction

In the process chains dedicated to the manufacturing of surgical implants, like hip or knee replacements, machining operations are carried out after the hot forging process to obtain geometrical features characterized by specific geometrical tolerances and surface peculiarities. In general, the forming process allows obtaining near-net shape components, which, afterwards, are subjected to semi-finishing turning and/or milling operations whose effects on the surface integrity of the final products cannot be neglected. In the biomedical field, machining operations are currently conducted adopting traditional mineral or natural lubricating solutions, requiring costly cleaning and sterilization steps. Furthermore, recent studies have proved that cutting fluids have an economical impact as high as 17% of the total manufacturing costs [1]. Therefore, alternative lubricating strategies, such as Minimum Quantity Lubrication (MQL) , cryogenic and dry machining [2], are gaining more and more interest for permitting the overall decrease of the manufacturing costs of surgical implants. Besides the influence on the tool wear, these alternative lubrication strategies are recognized to strongly affect the machined part surface integrity. Several works have been carried out to investigate the surface integrity of Nickel and Titanium-based superalloys under different lubricating strategies [3]. As an example, in [4], it was found that adopting a cutting speed of 60m/min in dry turning of Inconel 718, resulted in comparable results in terms of residual stresses and surface roughness with wet turning. Zhou et. al [5] found that the application of a 5% semi-synthetic emulsion reduced surface damages of Inconel 718 under high speed turning conditions with ceramic tools. In literature, no exhaustive works can be found concerning the study of the effects machining processes on the surface integrity of CoCrMo alloys, commonly used in the biomedical field, especially under dry lubricating

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conditions. To overcome this lack, the paper presents an experimental study devoted to the analysis of the effects of semi-finishing turning parameters on the surface integrity of ASTM F1537 CoCrMo bars. The aim of the work is to test the feasibility of dry turning of a CoCrMo alloy by adopting a commercial coated insert. The effect of the cutting parameters was evaluated for a fixed turning length corresponding to a steady state of the tool wear. The surface integrity was characterized in terms of surface roughness, surface topography, material microstructure alterations, and residual stresses along the hoop and axial directions. Even if the applied methodology for the surface integrity analysis is already consolidated in the scientific community, the paper presents some new interesting results that will prove the feasibility of machining this difficult-to-cut metal in dry conditions, still preserving its surface integrity.

2. Experimental procedure

The workpiece material evaluated in this study is the wrought alloy ASTM F1537 CoCrMo, with a chemical composition including 26% Cr, 6% Mo, 0,14% C, 0,75% Fe, 1 % Ni, 0,25% N, and balance of Co. The as delivered alloy was supplied in a 3 meters and 29 mm diameter warm worked bar (UTS 1172 MPa, 35 HRC).

Semi-finishing turning tests were conducted on a Mori Seiki® NL 1500 CNC lathe adopting a single layer PVD coated TiAlN carbide cutting tool, namely the Sandvik®

CNMG 120404 SM 1105, mounted on a Sandvik® PCLNR/L tool holder with a tool cutting edge angle Kr of 75°. The experimented works consisted of four test trials adopting two values for the cutting speed, 40 and 60m/min and two for the feed rate, 0.1 and 0.15 mm/rev, the depth of cut was kept constant and equal to 0.25 mm, no lubricants have been applied for all trials. The test specimens were machined starting from 29 mm diameter and 300 mm long round bars, and before realizing the turning operation, a 2 mm width surface layer was removed in order to eliminate possible surface defects.

The machined surface integrity was evaluated for each cutting condition for a steady state level of the tool wear corresponding to 3 minutes of turning. At that tool wear stage, a piece of the machined bar was cut to make further investigations.

3. Result and discussion

3.1. Surface topography

The machined surface topography was evaluated by

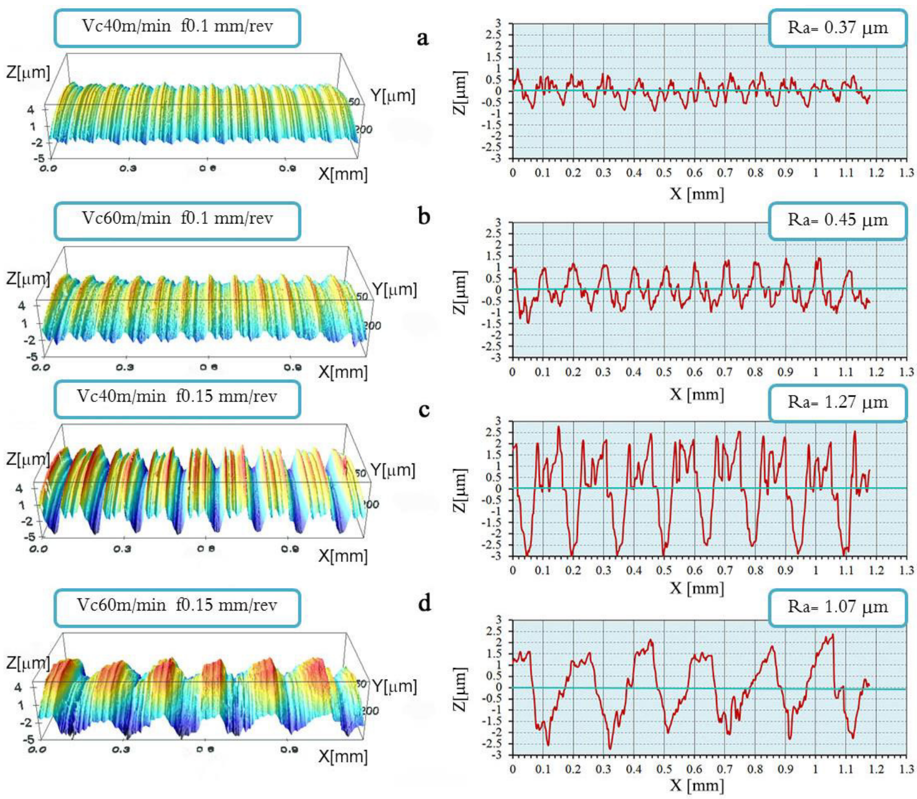

Fig. 1 Effect of the cutting parameters on the machined surface topography after 3 minutes of dry turning.

means of a Sensofar® Plu Neox optical 3D profiler. The digitalized scanned surfaces are presented in Fig. 1 on the left hand side, whereas on the right hand side the profiles of the machined surfaces obtained via software making a cross section of the digital scanned surfaces in correspondence to their centres, parallel to the axis of turning, are shown. In the same figure, as a conventional parameter to characterize the surface quality, the surface roughness R_a is reported, which was measured by means of a Taylor Hobson-Subtronic 25® portable roughness tester. With regard to the 3D images, the cutting parameters induce significant variations in terms of surface texture. The feed rate determinates the major alterations on the surface topography and profile: in particular, at increasing the feed rate from 0.1 to 0.15 mm/rev for a cutting speed of 40m/min, deeper grooves and sharper peaks resulted, which may negatively affect the fatigue and tribo-corrosion resistance of the final products. Considering the maximum peak to valley height roughness parameter R_t, defined by the ISO standard 4287–1997 [6], at increasing the feed rate from 0.1 to 0.15 mm/rev, an average increment from 3 to 5 μm is measured for both of the cutting speeds.

The smoothest surface resulted for a feed rate of 0.1 mm/rev, while for a feed rate of 0.15 mm/rev, the surface roughness resulted not useful for biomedical applications. The cutting speed effect resulted to be influential on the shape of the feed marks: at increasing the cutting speed to 60 m/min, a more uniform surface profile resulted, which may be attributed to the lower cutting edge chipping that was observed for a cutting speed of 60 m/min. Plastic deformation and material side flow [7] along the feed marks can be observed in Fig. 1(a) and (b) and (c) left, similarly to what observed in [6] during dry turning of Inconel 718.

3.2. Surface defects

Surface profilometry gave geometrical and metrological information concerning the turned surfaces, but to investigate the surface defects at higher level of accuracy or at lower scale, other methodologies may results more appropriate. Scanning Electron Microscopy analysis of the machined surfaces were carried out by several researchers on Titanium and Nickel basealloys [3], for the most part concerning superalloys used in the aerospace field, such as Inconel 718 and Ti6Al4V .

With the aim to fill the lack of literature and give a more exhaustive investigation on surface texture and quality, a SEM analysis of the Cobalt alloy turned surfaces was performed by means of a FEI QUANTA 450® SEM. Typical examples of observed surface damages are shown in Fig. 2, at different levels of magnification. No chatter marks were observed on the turned surfaces, since no chattering occurs for all the tested cutting conditions. A considerable variation in the density and morphology of the surface damages was observed in this study, being associated with the cutting parameters, namely cutting speed and feed rate, as found in [8] for Inconel 718. At the investigated stage of tool wear, the cutting speed mainly affected the coarse scale surface damages as can be observed in Fig. 3; in particular, at increasing cutting speed, a higher density of feed mark irregularities, such as tears, interrupted feed

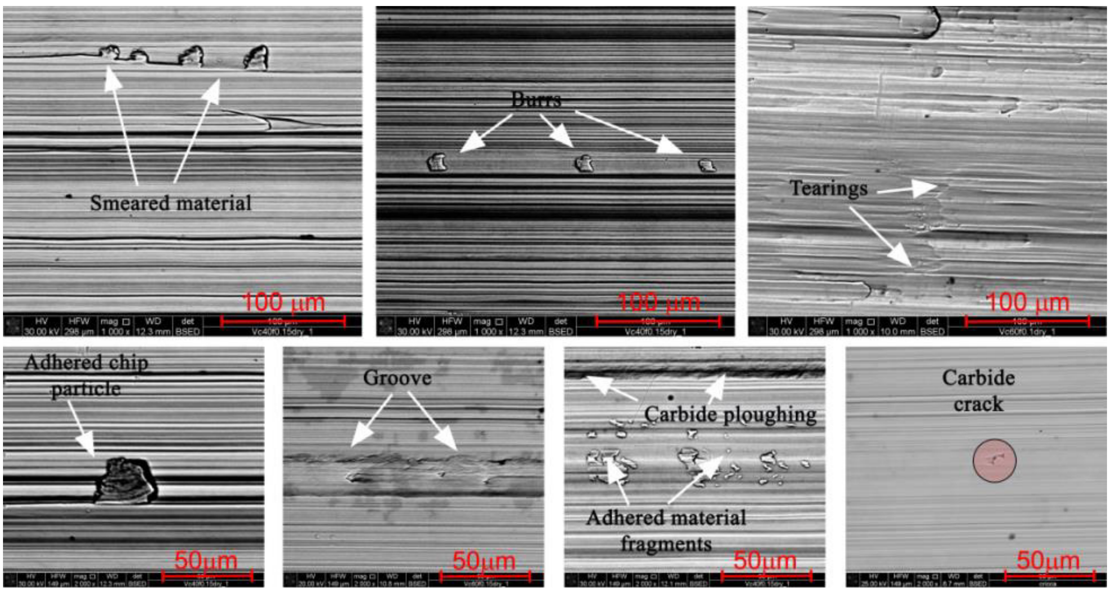

Fig. 2. SEM images of the main surface defects found in dry turning of ASTM F1537 CoCrMo after 3 minutes.

marks and grooves, are observed at the same level of magnification, since the cutting temperature increases at increasing cutting speed making the workpiece material more prone to plasticization. At 3 minutes of turning, the predominant tool wear mechanism is the adhesion, with significant amount of adhered material on the rake face.

For a cutting speed of 40 m/min, more cutting edge chipping occurred mainly affecting those surface damages correlated with the tool substrate carbide particles.

For the lower cutting speed, a higher density of long grooves parallel to the cutting speed direction was observed, formed as a consequence of the plowing effect of the hard tungsten particles that are removed from the tool rake and flank faces by the chip flow and by the rubbing effect of the fresh workpiece surface. These hard particles are not able to deform plastically so that they generates long grooves and tears on the machined surface at the next tool pass.

The surface chemical composition mapping analysis performed by means of the EDS-SEM detector (see Fig. 4) confirms the presence of tungsten particles into the surface layers, but no sensible variations were measured at varying cutting parameters. Even if the investigated Cobalt alloy presents hard and brittle $M_{23}C_6$ carbide particles in the matrix, the high plasticity induced by dry turning in the surface material reduced the presence of micro cracks, tears and breakage of carbides. On the other hand, the feed rate influences the chip morphology obtained during the first minutes of turning; for a feed rate of 0.1 mm/rev, short helical chips formed, while for a feed rate of 0.15 mm/rev long helical chip resulted, provoking chip entanglements around the workpiece and thus causing random scratches on the machined surface.

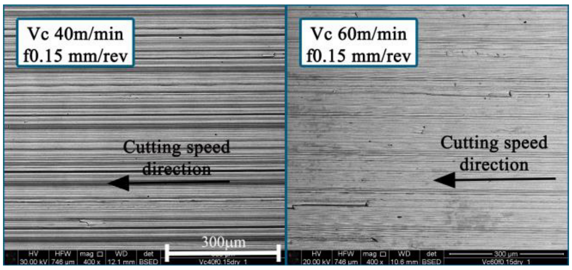

Fig. 3. Effect of the cutting speed on coarse scale surface defects.

At the highest level of feed rate, a sensible increment of burrs and adhered chip fragments were noted on the machined surfaces, while for both levels, smeared materials appeared between the feed marks, being the adhered material on the flank face.

3.3. Residual Stresses

Machining operations generally induce residual stresses through the outer layer of the workpiece machined surfaces, as proved in many researches [9]. In order to evaluate the feasibility of dry turning the F1537 CoCrMo, the evaluation of the stress state of the deformed material volume is of primary importance. The residual stresses present potential risks in terms of crack initiation, propagation and, as regards surgical implants, they also affect their tribo-corrosion resistance. The residual stresses on the machined surfaces was analysed by means of the XRD technique using the $\sin^2\psi$ method [10]. The XRD analysis was carried out on an Enixè® TNX diffractometer, by employing the parameters shown in Table 1.

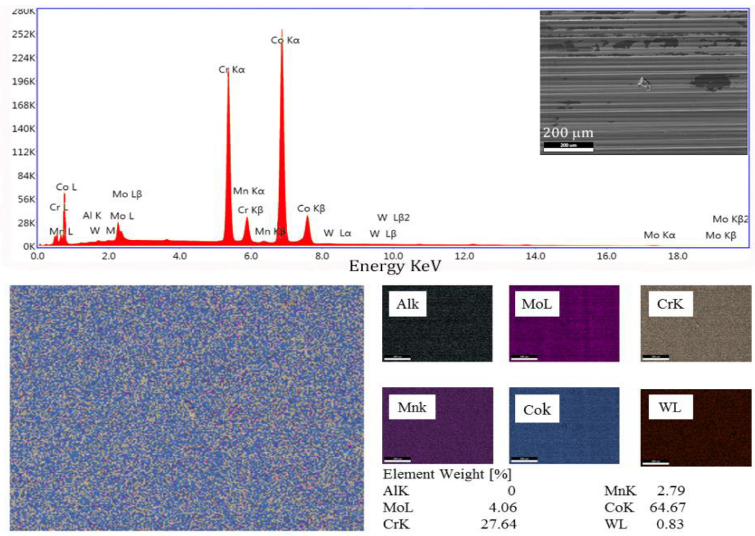

Fig. 4. Zone mapping (EDS) of a 0.4x0.6mm^2 area on the turned surface adopting a cutting speed of 40m/min and a feed rate of 0.15 mm/rev.

Table 1. Parameters for the XRD analysis.

Radiation	CrKα
Collimator Diameter (mm)	1
X-Ray elastic constants2θ(MPa^{-1})	S1-1.21x10^{-6} S2-5.42x10^{-6}
Number of ψ angles	9
Bragg Angle 2θ (Deg)	132.025
Current	85 μA

In order to evaluate the stressed state in depth, starting from the surface, successive layers of material were removed by electro-polishing to avoid the modification of machining- induced stresses. Even dough a disagreement is found in literature concerning the results obtained on residual stress measurements [3], in many cases a knee profile has been measured for both Titanium and Nickel alloys. In these cases, a compressive peak is reached at a depth of 25 to 75 μm, while on the surface a tensile peak is generally found [3]. In this work, the value of radial and axial residual stresses are presented in correspondence of the surface and for a depth of 50 μm, as an interesting value considering the results present in literature. Figs. 5 and 6 show that for all cutting conditions, at 3 minutes of turning both radial and axial residual stresses are always compressive, higher values are found on the surface than at a depth of 50 μm despite for an adopted cutting speed of 60m/min and a feed rate of 0.1 mm/rev. At increasing the feed rate, an increment of both axial and radial residual stresses resulted, while the cutting speed had an inverse effect reducing the stress levels for both directions, this may be attributed to the thermal softening that increases at increasing the temperatures with the cutting speed. At a depth of 50 μm beneath the turned surface, the compressive stresses are still high despite a general reduction is observed in comparison with surface value.

3.4. Micro-hardness and sub-surface microstructure

Dry turning of ASTM F1537 induced compressive residual stresses into a surface layer for all the tested cutting conditions. In order to carry out further investigations on the microstructural effects, micro-hardness measurement were performed by means of a Leitz Durimet™ micro-hardness tester with a load of 50 gr for 30 s. In many works present in literature dealing with the machinability of Nickel base and Titanium base superalloys [3], a micro-hardness gradient has been found along the radial direction. Inconel 718, is characterized by intense work hardening tendency when subjected to machining processes, inducing in many cases compressive residual stresses and hardening gradients from the surface to the bulk material.

Co base superalloys present a behaviour comparable to that of the Nickel base super alloys, showing strain hardening behaviour when subjected to plastic deformation [11]. The micro-hardness profiles presented in Fig.7 confirmed this similarity. An increase in the micro-hardness can be observed for all the tested cutting

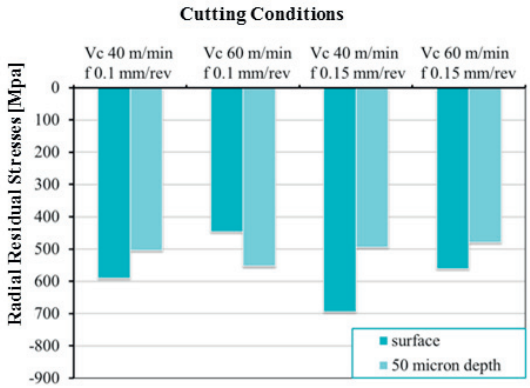

Fig. 5. Radial residual stresses after 3 minutes of dry turning.

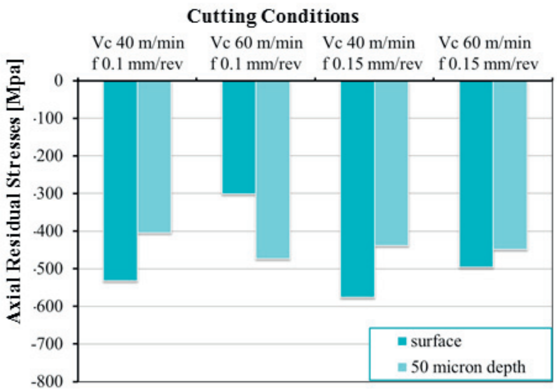

Fig. 6. Axial residual stresses after 3 minutes of dry turning.

conditions: this can be attributed to thermal and mechanical loads on the surface volume raising the strain hardening effect. The feed rate provokes the major effects on the surface hardening, resulting in an increment from the bulk value of 510 HV0.05 to 780 HV0.05 for a cutting speed of 60m/min and a feed rate of 0.15 mm/rev, it may be induced by higher mechanical load and higher temperatures generated with higher feed rates.

An example of the sub-surface microstructure is shown in Fig. 8: it can be seen that a 25 to 35μm width sub-surface layer is affected by grain refinement and grain deformation along the cutting speed direction, but no sensible variations can be appreciated among the tested cutting conditions. Slight differences in terms of induced material strain hardening among the cutting tests at 3 min of turning may explain this phenomena.

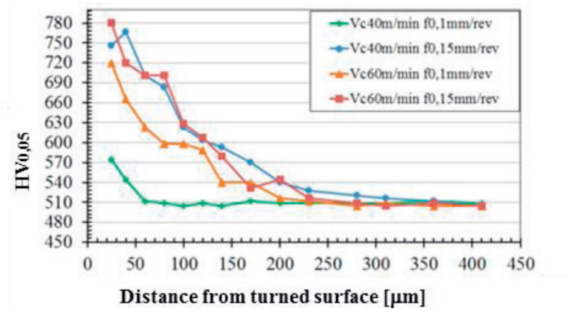

Fig. 7. Effect of cutting parameters on micro-hardness after 3 minutes of turning.

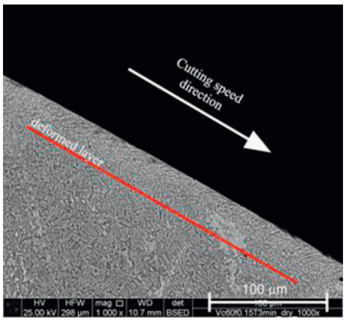

Fig. 8. Effect of turning on the sub-surface microstructure.

4. Conclusions

This paper presents the experimental results in terms of surface integrity when turning a CoCrMo alloy in dry conditions regarding to biomedical applications.

Experimental observations reported in this study point out that dry turning is a pursuing lubricating strategy that may generate economic advantages for surgical implants manufacturers due to the reduction of cleaning processes and the amount of used lubricant to dispose with a view to sustainability. The effects of the cutting speed and feed rate on surface integrity were evaluated in terms of surface topography, surface roughness, residual stresses, micro-hardness measurements, and microstructure alterations. Further studies will analyse different cutting conditions and the effect of the tool wear on surface integrity to fill the lack of literature. The main outcomes can be summarized as follows:

The feed rate played the major role on the surface roughness: smoother surfaces resulted for a feed rate of 0.1 mm/rev, while not regular surfaces resulted for a feed rate of 0.15 mm/rev. The cutting speed effect influenced the shape of the feed marks, and more uniform surface profiles resulted for a cutting speed of 60 m/min due to less chipping and notching of the cutting edge.

For a cutting speed of 40 m/min, a higher density of long grooves due to the tungsten carbide particles resulted, while at higher cutting speed a higher density of folds, tears and interrupted feed marks resulted due to higher temperature. At increasing the feed rate, the chip morphology changed and entanglement around the workpiece resulted, therefore a higher density of adhered chip fragments on the surface resulted.

XRD analysis showed that high compressive stress resulted on the surface for all the cutting conditions, and a small reduction of stress level is observed at a depth of 50 μm. The feed rate increment tends to increase the compressive stresses due to higher strain rate, while the cutting speed has an inverted effect due to the increment of the cutting temperature.

The effect of the turning process resulted in a deformed sub-surface layer along the cutting direction, and a grain refinement is appreciable. The strain hardening induced a surface hardening of the material with a radial gradient, which increases at increasing the cutting parameters.

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